

## **Biological Removal of Dyes from Wastewater: A Review of Its Efficiency and Advances**

**Kuok Ho Daniel Tang<sup>1\*</sup>, Noura M. Darwish<sup>2</sup>, Abdullah M. Alkahtani<sup>3</sup>, Mohamed Ragab AbdelGawwad<sup>4</sup>, Peter Karácsony<sup>5</sup>**

<sup>1</sup> Environmental Science Programme, BNU-HKBU United International College, Zhuhai, China

<sup>2</sup> College of Science, Ai Shams University, Cairo, Egypt.

<sup>3</sup> Department of Botany and Microbiology, College of Science, King Saud University, P.O. 2455, Riyadh 11451, Saudi Arabia.

<sup>4</sup> Genetics and Bioengineering, Faculty of Engineering and Natural Sciences, International University of Sarajevo, 71210 Sarajevo, Bosnia and Herzegovina.

<sup>5</sup> University Research and Innovation Center, Óbuda University, Budapest, Bécsi út 96/B, 1034, Hungaria.

\*Correspondence: daniel.tangkh@yahoo.com

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**ABSTRACT:** Biological removal of dyes has been advocated due to its simplicity, cost-effectiveness, and low operational requirements in comparison to physicochemical methods of treating dye effluents. This paper aims to compare the efficiency of biological removal of dyes using bacteria, algae, and fungi, including yeasts, besides presenting the recent advances in the field. This paper reviewed scholarly articles published mainly between 2010 and 2021. It found bacteria could degrade a myriad of dyes. Different bacteria could degrade the same dye with different efficiencies. Similarly, one bacterial species could degrade multiple dyes with varying efficiencies. Though regarded as having a faster rate of dye biodegradation than fungi, this review finds bacteria to have comparable performance to fungi in decolorizing dyes, and it is worth mentioning that a few yeast species were reported to have very high efficiency in decolorizing dyes. Mixed bacteria or bacteria-fungus cultures were generally found to have better dye-decolorizing efficiency than pure cultures. Algae have relatively lower efficiency than bacteria and fungi in decolorizing dyes and might require longer contact time. New advances such as genetic engineering as well as immobilization of microorganisms and enzymes could improve the efficiency of dye biodegradation. Nonetheless, before biological removal of dyes can be feasibly applied, there are limitations that need to be overcome. Major limitations include the inconsistent performance of various organisms in decolorizing dyes; the complexity of optimization; inability to completely decolorize dyes; potential formation of toxic by-products upon decolorization of dyes; safety concerns of immobilization materials; and cost and technical feasibility of biological removal of dyes. This review has the significance of highlighting the important bottlenecks of the current biological dye removal technology, which could pave the way for breakthroughs in this domain of research.

**KEYWORDS:** Effluents; bacteria; fungal bioremediation; yeast; algae

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## 1. Introduction

Synthetic dyes are widely used in multiple industries, particularly the textile, paint, and printing industries. The textile industry not only tops the chart of dye utilization, it also produces the largest amount of dye effluents, approximately 100 tonnes per year [1]. The voluminous effluents generated are contributed mainly by the water needed to disperse or dissolve the dyes for textile-dyeing in the industry [2]. The dye mixtures or solutions are used to impart colors on textiles, but since not all the dyes bind to the textiles, the excessive dyes are discharged through waste streams from the industry [3]. It has been estimated that up to 80% of dyes and the associated chemicals are adsorbed depending on the substrates, and fabrics could only adsorb up to 25% of dyes [4]. The excessive dyes enter the dye effluents, which typically consist of a mixture of chemicals used by the textile industry such as wetting agents, acetic acid, ammonium sulphate, caustic soda, dispersing agents, hydrosulfates, and organic solvents [5].

**Table 1.** Characteristics of different classes of synthetic dye

Class	Example	Ionic Nature	Solubility	Application pH	Use
Acid	Acid Blue 45, Acid Yellow 42	Anionic	Water-soluble	4-5	Wool, silk, nylon, acetate, acrylic
Basic	Basic Yellow 28	Cationic	Water-soluble	5-6	Wool, cotton (with mordant), silk, nylon
Direct	Direct Blue 199, Direct Yellow 142	Anionic	Depends on types	7	Mainly cellulosic fabrics (without mordant)
Disperse	Disperse Blue 73, Disperse Red 79	Non-ionic	Slightly water-soluble	4-5	Acetate, nylon, cellulose fibers, polyester
Reactive	Reactive Red 195, Reactive Black 5	Anionic	Depends on types	11-13	Mainly for cotton
Sulfur	Sulfur Black, Sulfur Brilliant Green	Non-ionic	Insoluble	10-11	Linen, jute, cotton
Vat	Vat Brown-5, Vat Blue-4	Non-ionic	Insoluble, soluble leuco salts	12-13	Cotton, wool

Note: Mordants are used to improve the fastness and affinity of a dye to a fabric. Examples of mordants are metal salts, tannins and tannic acid or oils. To increase the affinity of cotton to basic dyes, treatment with mordant is required.

Synthetic dyes are diverse and they are broadly categorized into acid, basic, direct, disperse, reactive, sulfur, and vat [6]. Taking acid dyes, for instance, they are commonly applied to cosmetics, acrylic, nylon, silk, and wool as acidic dye solutions. Acid Yellow 36 is a type of acid dye [7]. Basic dyes or cationic dyes are mostly found in inks, paper, polyacrylonitrile, and polyester, and an example of a basic dye is methylene blue [8]. Vat dyes such as Vat Blue 4 are water-insoluble dyes typically added to cotton, rayon, and cellulosic fibers through a solubilizing process of reduction followed by oxidation [6]. Table 1 shows the characteristics of the classes of synthetic dyes. Dyes can also be categorized based on functional groups and chromophores. Azo dyes represent a large group of dyes with an R-N=N-R' functional group, where R and R' are commonly aryls [9]. They are typically used for textiles, leather goods, and food. The overarching azo dyes can be further classified based on the classes in Table 1, namely acid, basic, direct, disperse, and vat, which are fundamentally the methods by which different dyes bind to a material [10]. Sulfur dyes, however, constitute another group of dyes containing sulfur linkages as part of their chromophore, e.g. sulphide (-S-), disulphide (-S-S-), and polysulphide. Sulfur dyes are typically non-ionic, not water soluble and are commonly used on linen, cotton and jute. Examples of sulfur dyes are Sulfur Black and Sulfur Brilliant [4].

Generally, all synthetic dyes pose hazards to the environment, and this is complicated by the diverse types of dyes used. Dye effluents, which are mixtures of multiple chemicals and dyes, therefore result in multiple hazards to humans and the biota. The colors that taint natural waterbodies contaminated by dye effluents not only result in aesthetic degradation but also reduce light penetration, hence the rate of photosynthesis by aquatic flora [11]. In addition, the effluents contain high levels of chemical oxygen demand (COD) and biochemical oxygen demand (BOD), which strip the waterbodies of dissolved oxygen and the availability of oxygen to the biota [12]. Synthetic dyes could be inherently toxic, mutagenic, and carcinogenic, and their persistent nature could prolong their ecotoxicity [13]. Such persistence may also increase their exposure to biota, thus increasing the likelihood of bioaccumulation and biomagnification along the food chain [14]. Water containing azo dyes with low affinity (15–50%) for fabric has been reported in the dye effluents of the textile industry in developing countries. The receiving waterbodies are often used for agricultural irrigation [15]. The entry of these dyes into agricultural soil clogs soil pores and affects the germination and growth of plants [15]. Pollution of waterbodies with the dyes disrupts the water supplies of communities that rely on the waterbodies as a direct source of water. Consumption of dye-polluted water might cause direct effects such as excessive sweating, confusion, mouth burns, nausea, and methemoglobinemia, in addition to long-term health effects [16].

Due to the detrimental effects of dyes on humans and biota, the removal of synthetic dyes from dye effluents has received central attention. National and international legislations have been established to regulate discharges of dye effluents into the environment, often as part of wastewater discharge regulation [17]. The Zero Discharge of Hazardous Chemicals (ZDHC) Program lists 11 priority chemicals to be eliminated from wastewater, including azo dyes. The program has garnered the participation of major players in the textile industry in the effort to develop uniform industry guidelines, which led to a review of the textile industry's wastewater discharge quality standards [18]. Nonetheless, the progress in framing regulations for dye effluents has not been encouraging and is not uniform across countries. For instance, only a few countries have specific regulations for dye effluents, for instance the Discharge Standards of Water Pollutants for Dyeing and Finishing of the Textile Industry (GB 4287-2012) of China [19], the Textile Mills Effluent Guidelines of the United States [18], and Standards for Effluents from the Textile Industry (S. No. 92) of India [18].

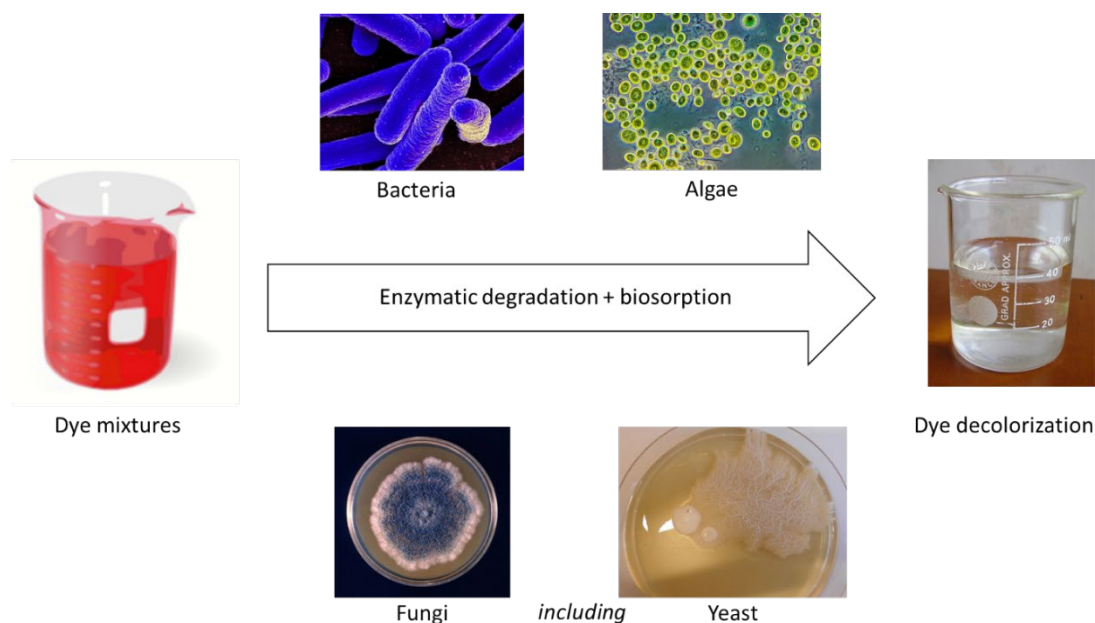
Multiple strategies have been proposed to remove dyes from wastewater, typically consisting of physical, chemical, and biological treatments [20]. The physicochemical removal of dyes from effluents involves high electricity and chemical requirements while producing abundant sludge that needs to be properly disposed of [12]. This is evident in the water treatment plants set up to treat dye effluents, which frequently demand high operational, power, and chemical requirements [12]. In view of this, biological treatment has been considered as a feasible alternative to physicochemical treatment owing to its simplicity, incurrence of lower cost, and environmental friendliness [21, 22, 23]. This review, therefore, presents the recent developments in the biological removal of synthetic dyes by bacteria, fungi, and algae, particularly the efficiency, advantages, and limitations. A distinction has been made between yeast and other fungi due to its unicellular feature.

## 2. Materials and Methods

This paper reviews more than 80 scholarly articles on the biological removal of synthetic dyes from dye effluents. The articles were searched from journal databases, namely Scopus, Web of Science, ScienceDirect, and ProQuest with keywords comprising bacteria, microorganisms, algae, fungi, dye removal, and bioremediation of dye effluents. The search was conducted predominantly on literature published in the last 11 years (2010–2021) to give an updated overview of the area [24, 25]. However, in instances where there was a need to provide the theoretical background and historical perspectives, literature published earlier was also included.

## 3. Results and Discussion

Biological removal of dyes involves the use of living organisms such as bacteria, algae, and fungi, including yeast, or the enzymes produced by the organisms to biodegrade dyes [26] (Figure 1). Dye biodegradation with bacteria and fungi can be carried out in pure or mixed cultures. The use of immobilized enzymes is gaining popularity due to the better stability, efficiency, and reactivity of immobilized enzymes. Table 2 shows the removal of dyes by bacteria, fungi, and algae, either in pure or mixed culture.

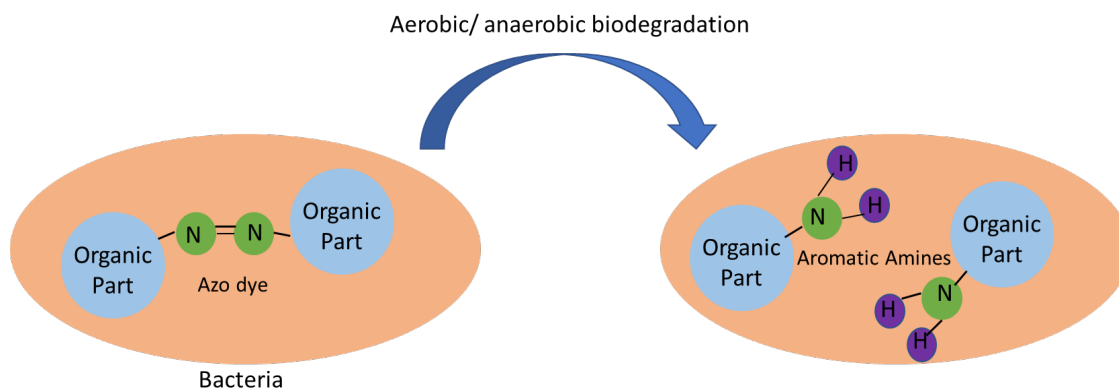


**Figure 1.** Decolorization of dyes using bacteria, fungi and algae

### 3.1. Removal of Dyes with Bacteria

Owing to the ability of bacteria to survive in a wide range of environmental conditions, particularly under various ranges of pH, temperature, and oxygen, they are widely employed in wastewater treatment. Bacteria generally confer a faster rate of dye biodegradation than fungi [27] and have been found to be able to convert azo dyes to aromatic amines under anaerobic conditions, which are otherwise recalcitrant to aerobic biodegradation [28] (Figure 2). However, there are bacteria that could decolorize dyes more efficiently under aerobic conditions due to the presence of azoreductases, i.e., enzymes that could reduce azo bonds. For

instance, under aerobic conditions, *Micrococcus* sp. was reported to decolorize reactive dyes within 6 hours, and this would take 24 hours under anaerobic conditions [29].



**Figure 2.** Degradation of azo dye by bacteria

Bacteria have been found to be able to degrade multiple dyes, ranging from Methyl Red, Reactive Blue 59, Reactive Red, Naphthol Green B, Acid Black 24, to Remazol Navy Blue, Congo Red, and Metanil Yellow (Table 2). Typically, the duration of dye decolorization by bacteria ranges from 2 hours to 96 hours, with an efficiency of 75% to 100%. Numerous bacteria were reported to be able to degrade the same dye for instance, decolorization of Methyl Red by *Sphingomonas paucimobilis*, *Nesterenkonia lacusekhoensis*, and *Lysinibacillus fusiformis*, but at different rates and efficiency (Table 2). All three bacteria were able to achieve > 95% decolorization of Methyl Red [30, 31, 32]. In addition, the efficiency of dye decolorization might vary between dyes. Only 76% of Orange II was decolorized by *Staphylococcus aureus* in 48 hours [33], in comparison to 94% of Acid Orange by *Staphylococcus hominis* in 60 hours [34] (Table 2). Nonetheless, the comparison might be constrained by the different species of *Staphylococcus* used. In a separate study, *Staphylococcus aureus* was reported to only be able to decolorize 2% of Acid Orange 10 after 3 days as compared to 76% of Orange II in 2 days, thus suggesting that the same bacterium might demonstrate widely varied decolorization efficiency for different dyes [35].

It is also noteworthy that the dye decolorization efficiency could be affected by the type of culture. In a few instances, mixed bacteria cultures achieved complete decolorization of dyes, e.g., 100% decolorization of Remazol Brilliant Violet 5R by a mixture of *Bacillus* sp., *Staphylococcus* sp., *Escherichia* sp., *Enterococcus* sp., and *Pseudomonas* sp. [36] and 100% decolorization of Golden Yellow HER by a mixed bacterium and yeast-like fungus culture (*Galactomyces geotrichum* and *Brevibacillus laterosporus*) [37] (Table 2). However, in other instances, mixed cultures did not seem to produce complete or exceptionally high dye decolorization, e.g., 80% decolorization of Reactive Orange 16 by mixing *Acinetobacter* sp. and *Klebsiella* sp. [38], and 80% decolorization of Reactive Navy Blue by a mixed culture of bacteria of *Pseudomonas* sp. and a fungus scientifically named *Aspergillus ochraceus* [39]. Therefore, the dye decolorization efficiency of mixed bacteria or bacteria-fungi cultures needs further confirmation, particularly by comparing it with that of the pure culture for the same dye. In the study of Kadam et al., mixed culture with a decolorization efficiency of 80% to 92% was higher than *Pseudomonas* sp. alone (78%) and *Aspergillus ochraceus* alone (61%) [39]. Holkar et al. suggested that mixed cultures contain multiple bacteria with different enzymatic reactions that could work together to achieve higher dye degradation by attacking different

parts of a dye molecule [21]. In bacteria-fungi mixed cultures, the initial degradation of complex dye molecules might be carried out by fungi, whereas bacteria play their role subsequently by totally removing organic carbon [40]. The ratios of individual microorganisms in a mixed culture might affect dye decolorization efficiency. Congo Red was found to be completely decolorized in a mixed culture with 0.02% *Sphingomonas paucimobilis*, 0.45% *Bacillus* sp., and 0.51% *Staphylococcus epidermidis* [30].

**Table 2.** Efficiency of dye decolorization with pure or mixed cultures of bacteria, fungi, yeasts, and algae

Dye	Scientific Name	Organism and Culture	Duration of Biodegradation	Efficiency (%) (based on decoloratization)	Reference
Methyl Red	<i>Sphingomonas paucimobolis</i>	Bacteria, pure culture	10 hrs	98	[30]
	<i>Nesterenkonia lacusekhoensis</i>	Bacteria, pure culture	16 hrs	97	[31]
	<i>Lysinibacillus fusiformis</i> WIB6	Bacteria, pure culture	2 hrs	96	[32]
Methyl Violet	<i>Bjerkandera adusta</i>	Fungus, pure culture	24 hrs	94	[41]
Orange II	<i>Staphylococcus aureus</i>	Bacteria, pure culture	48 hrs	76	[33]
Reactive Blue 59	<i>Alishewanella</i> sp.	Bacteria, pure culture	6 hrs	95	[42]
Reactive Red 141	<i>Bacillus lentus</i> BI377	Bacteria, pure culture	6 hrs	99	[43]
Reactive Red 184	<i>Halomonas</i> sp. strain A55	Bacteria, pure culture	24 hrs	96	[44]
Reactive Red 21	<i>Pseudomonas aeruginosa</i>	Bacteria, pure culture	48 hrs	81	[45]
Reactive Navy Blue	<i>Pseudomonas</i> sp. and <i>Aspergillus ochraceus</i>	Bacteria and fungus, mixed culture	24 hrs	80	[39]
Reactive Orange 16	<i>Acinetobacter</i> sp. and <i>Klebsiella</i> sp.	Bacteria, mixed culture	72 hrs	80	[38]
Reactive Yellow 3 RN	<i>Aphanocapsa elachista</i>	Alga, pure culture	7 days	49	[46]
Reactive Black 5	<i>Chlorella vulgaris</i>	Alga, pure culture	10 days	80	[47]
	<i>Armillaria</i> sp. F022	Fungus, pure culture	96 hrs	80	[48]

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Dye	Scientific Name	Organism and Culture	Duration of Biodegradation	Efficiency (%) (based on decoloratization)	Reference
	<i>Trichosporon akiyoshidainum</i> HP2023	Yeast, pure culture	24 hrs	100	[49]
	<i>Sterigmatomyces halophilus</i> SSA1575	Yeast, pure culture	24 hrs	98	[50]
Napthol Green B	<i>Shewanella oneidensis</i> MR-1	Bacteria, pure culture	24 hrs	95	[51]
Acid Black 24	<i>Bacillus halodurans</i> MTCC 865	Bacteria, pure culture	6 hrs	90	[52]
Acid Orange	<i>Staphylococcus hominis</i> RMLRT03	Bacteria, pure culture	60 hrs	94	[34]
	<i>Myrothecium roridum</i>	Fungus, pure culture	24 hrs	80	[53]
Acid Red 18	<i>Paraconiothyrium variabile</i>	Fungus, pure culture	15 mins	97	[54]
Remazol Navy Blue	<i>Bacillus pumilus</i> HKG212	Bacteria, pure culture	30 hrs	>95	[55]
Remazol Brilliant Violet 5R	<i>Bacillus</i> sp., <i>Staphylococcus</i> sp., <i>Escherichia</i> sp., <i>Enterococcus</i> sp. and <i>Pseudomonas</i> sp.	Bacteria, mixed culture	18 hrs	100	[36]
Congo Red	<i>Pseudomonas extremorientalis</i> BU118	Bacteria, pure culture	24 hrs	75	[56]
	<i>Geobacillus thermocatenulatus</i> MS5	Bacteria, pure culture	32 hrs	99	[57]
	<i>Geotrichum candidum</i>	Yeast-like fungus, pure culture	48 hrs	85	[58]
Azure-B	<i>Serratia liquefaciens</i>	Bacteria, pure culture	48 hrs	90	[59]
Synazol Red 6HBN	<i>Alcaligenes aquatilis</i> 3c	Bacteria, pure culture	96 hrs	82	[60]
Golden Yellow HER	<i>Galactomyces geotrichum</i> and <i>Brevibacillus Laterosporus</i>	Bacteria and yeast-like fungus, mixed culture	24 hrs	100	[37]
Disperse Red 1	<i>Microbacterium</i> sp., <i>Leucobacter albus</i> , <i>Klebsiella</i> sp. and <i>Staphylococcus arlettae</i>	Bacteria, mixed culture	72 hrs	80	[61]

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Dye	Scientific Name	Organism and Culture	Duration of Biodegradation	Efficiency (%) (based on decoloratization)	Reference
	<i>Chlorella vulgaris</i>	Alga, pure culture	10 days	84	[47]
Disperse Orange 2RL	<i>Chlorella vulgaris</i>	Alga, pure culture	7 days	55	[62]
Metanil Yellow	<i>Lactococcus</i> and <i>Dysgonomonas</i>	Bacteria, mixed culture	6 hrs	96	[63]
Methylene Blue	<i>Ulva lactuca</i>	Alga, pure culture	110 mins	91	[64]
Direct Blue 71	<i>Chlorella vulgaris</i>	Alga, pure culture	10 days	78	[47]
Kiton Blue A	<i>Cyathus bulleri</i>	Fungus, pure culture	6 hrs	88	[65]
Scarlet RR dye	<i>Peyronellaea prosopidis</i>	Fungus, pure culture	5 days	85	[66]
Crystal Violet	<i>Bjerkandera adusta</i>	Fungus, pure culture	24 hrs	91	[41]
Malachite Green	<i>Bjerkandera adusta</i>	Fungus, pure culture	24 hrs	96	[41]

### 3.2. Removal of Dyes with Fungi and Yeasts

Fungi can remove dyes through biodegradation and/or biosorption. The abundance, cost-effectiveness, desirable mechanical properties, and chemical stability of fungi make them good candidates for biosorption of dyes, but fungal biosorption could be limited by increased temperature due to the decrease of active sites and surface for adsorption [67]. Examples of fungi which show the ability to adsorb dyes are *Cunninghamella elegans* [68] and *Trametes versicolor* [69]. Certain fungi, particularly filamentous fungi, can also secrete enzymes such as peroxidase and phenoloxidase [21]. According to Table 2, like bacteria, fungi can decolorize multiple dyes such as Reactive Black 5, Acid Orange, Congo Red, Kiton Blue A and Malachite Green. The dye decolorization efficiency of fungi ranges from 80% to 100% (with 100% reported in a mixed bacteria-fungus culture) over incubation durations ranging from 15 minutes to 5 days. It is noteworthy that *Paraconiothyrium variabile* could decolorize 97% of Acid Red 18 over a duration of 15 minutes [54] (Table 2).

Different fungi might have different decolorization efficiencies for the same dye, and similarly, the same fungus might decolorize different dyes with different efficiencies. *Bjerkandera adusta* had been shown to decolorize 96% of Malachite Green and 91% of Crystal Violet in 24 hours [41] (Table 2). A comparison between the efficiency of bacteria and fungi in decolorizing the same dye is not a straightforward one. For instance, a fungus called *Myrothecium roridum* was reported to decolorize 80% of Acid Orange in 24 hours, in contrast to 94% in 60 hours by *Staphylococcus hominis* [34, 53]. Given the longer incubation time for *Staphylococcus hominis*, it is hard to conclude that the bacterium has a higher efficiency than the fungus. Furthermore, decolorization studies of Congo Red revealed that bacteria



*Pseudomonas extremorientalis* and *Geobacillus thermocatenulatus* had efficiencies of 75% and 99% respectively and while yeast-like fungus *Geotrichum candidum* had an efficiency of 85% (Table 2) [56, 57, 58]. It seems that fungi are rather comparable to bacteria in terms of dye decolorization efficiency. Though relatively less common compared to bacteria and bacteria-fungus mixed cultures, fungi mixed cultures for dye removal had been studied. Krishnamoorthy et al. reported a mixed culture of *Dichotomomyces cejpai* MRCH 1-2 and *Phoma tropica* MRCH 1-3 could decolorize a maximum of approximately 97% of Congo Red, 87% of Methyl Red and 91% of Reactive Blue over 4 days after optimization of nutrient content [70].

Yeasts have exhibited the ability to decolorize dyes. They could propagate rapidly like bacteria and could survive in demanding environmental conditions. They typically adsorb dyes or degrade dyes enzymatically, similar to multicellular fungi [71]. Studies have shown yeasts to be good candidates for dye decolorization with high efficiency. *Sterigmatomyces halophilus* was found to decolorize 98% of Reactive Black 5 after only 24-hour incubation while *Trichosporon akiyoshidainum* completely decolorized Reactive Black 5 in the same duration (Table 2) [49, 50]. Their decolorization efficiencies were significantly higher than the 80% of *Armillaria* fungus over 96 hours [48]. Furthermore, *Galactomyces geotrichum* used in a mixed culture with bacteria *Brevibacillus Laterosporus* which could completely remove Golden Yellow HER, is a yeast-like fungus (Table 2) [37].

### 3.3. Removal of Dyes with Algae

The application of algae for dye removal has been explored due to its cost-effectiveness and potential for large-scale cultivation. Besides, the growth of algae does not seem to be inhibited in dye-contaminated water [46]. Similar to fungi and yeast, algae could remove dyes through biosorption or enzymatic reactions, such as the degradation of azo dyes by an azoreductase present in algae. According to Table 2, the algae studied could remove dyes at efficiencies ranging from 55% to 91% over 110 minutes to 10 days. *Chlorella vulgaris* has been widely studied and in most studies, it was found that *Chlorella vulgaris* was incubated for 7 to 10 days for dyes decolorization, a duration much longer than bacteria, fungi, and yeasts. For instance, *Chlorella vulgaris* recorded a decolorization efficiency of 80% for Reactive Black 5 over 10 days [47], in comparison to the 80% of *Armillaria* fungus over 96 hours [48] and 100% of yeast *Trichosporon akiyoshidainum* over 24 hours [49]. *Chlorella vulgaris* was only able to decolorize 55% of Disperse Orange 2RL in 7 days [62]. However, an alga called *Ulva lactuca* could decolorize 91% of Methylene Blue in just 110 minutes [64].

### 3.4. Advances in Biological Removal of Dyes

Genetic engineering has been receiving attention in advancing the biological removal of dyes, largely attributed to the limitations of conventional biological removal, which can rarely achieve complete biodegradation of dyes, and it requires extensive studies to identify the right organisms or combination of organisms for the degradation of certain dyes. Besides, optimizing biological dye removal requires voluminous permutations of conditions such as nutrients, pH, temperature, light, etc. Through genetic engineering, the stability and efficiency of dye biodegradation by microorganisms can be improved. This can be achieved by introducing the Azoreductase gene, azoK, derived from *Klebsiella pneumoniae* into *Escherichia coli* DH5 to produce *E. coli* BL21, which has a better ability to degrade Methyl Orange [72]. Similarly, *P.*

*pastoris* carrying a recombinant Lac gene from *Ganoderma lucidum* has an improved ability to degrade Methyl Orange [73]. A recombinant *E. coli* containing the Lac-like gene lac21 was able to degrade azo dyes over a wider pH range of 5–9 [74]. Azo dyes in wastewater have also been efficiently degraded by a recombinant *E. coli* DE3 formed by introducing the AzoG gene of *Halomonas* sp. into *E. coli* DH5 [63]. Besides, enhanced degradation of Remazol Black B and Methyl Red by an *E. coli* carrying a recombinant azoreductase gene from *Halomonas elongata* has been reported [75]. Genetical engineering has conferred upon microorganisms, particularly bacteria, an improved ability to degrade dyes either through better efficiency or enhanced tolerance to broader environmental conditions.

Immobilization of microorganisms for biodegradation of dyes is becoming increasingly popular due to its higher stability than free cultures and better tolerance to different environmental conditions. Microorganisms could be entrapped or attached to a support during immobilization [76]. A freshwater microalga, *Desmodesmus* sp., had been immobilized for the removal of Methylene Blue, and the immobilized alga achieved a maximum of 98.6% dye decolorization over 6 days [77]. An immobilized biosorbent derived from *Aspergillus niger* has also been applied to decolorize Malachite Green and an efficiency of 82.6% has been reported over 72 hours of contact time at pH 5.0 [78]. Furthermore, enzymes responsible for biodegradation of dyes within an organism can be separated and immobilized, thus forming immobilized enzyme complexes to degrade dyes. Immobilized enzymes have the benefits of better kinetic stability and recyclability [79]. For instance, laccase from *Trametes pubescens* has been successfully immobilized on genipin-activated chitosan beads, and the immobilized laccase could decolorize 77% of Acid Black 172 [80]. Also, immobilization of laccase derived from *Trametes versicolor* on carbon nanotube nanocomposites has been conducted where the immobilized enzyme could decolorize Congo Red with up to 96% efficiency [81].

### 3.5. Limitations of Biological Removal of Dyes

There are some obvious limitations in relation to biological removal of dye as below:

- a) Efficiency is widely variable [82]. Different organisms have different efficiencies in decolorizing the same dye, and the same organism might also have different efficiencies in decolorizing different dyes.
- b) The optimal conditions under which different organisms degrade dyes are different.
- c) Complete decolorization of dyes is rarely achieved, even with genetically engineered microorganisms, immobilized microorganisms, and immobilized enzymes.
- d) Optimization of operational conditions for large-scale application of biological dye removal might involve extensive testing of different operational parameters.
- e) While mixed cultures are more efficient in decolorizing dyes in some instances, there are enormous possible combinations of organisms and ratios of combinations for this purpose.
- f) In most studies, decolorization of dyes has been used to indicate the efficiency of dye removal. It is uncertain whether the dyes have been completely degraded to non-toxic substances or mineralized upon decolorization.
- g) The use of bacteria and fungi for the removal of dyes might present potential biological hazards, especially if the organism is also a pathogen.

- h) There is uncertainty about the ecotoxicity of dye metabolites produced by biological processes. While the metabolites could be harmless to the biodegrading organisms, they could be harmful to other organisms.
- i) The cost and technical feasibility of separating organisms, microorganisms, or enzymes for dye removal is questionable when compared to conventional biological wastewater treatment involving a consortium of microorganisms.
- j) The safety of immobilization technologies is a concern. The support used for immobilization could give rise to environmental and health concerns.

#### 4. Conclusions

In this review, various bacteria, algae, and fungi, inclusive of yeasts, have been found to demonstrate the ability to remove dyes, though at different efficiencies. Bacteria and fungi seem to be comparable in their performance in decolorizing dyes in terms of efficiency and duration. Certain yeasts demonstrate very high dye decolorization efficiency, such as *Trichosporon akiyoshidainum*, which can completely decolorize Reactive Black 5 in just 24 hours. Algae generally require longer contact or incubation times with dyes. *Chlorella vulgaris* has been commonly studied for its dye-decolorizing ability, which in most instances is below 90%. Mixed cultures, either mixed bacteria, mixed fungi, or mixed bacteria-fungi cultures, might offer improved efficiency of dye decolorization. The ratios of mixing and the species of organisms mixed could affect the efficiency. Genetically engineered organisms as well as immobilization of organisms or enzymes provide new options for decolorizing dyes with better efficiency, stability, and recyclability, but are uncertain in terms of safety, cost-effectiveness, and technical feasibility. Overall, biological removal of dyes also suffers from limitations such as operational uncertainties, widely variable or inconsistent performances, inability to completely remove dyes, complicated manipulation of variables for optimization and potential production of harmful by-products.

Future directions in this domain of study could continue to identify new organisms capable of degrading dyes and optimize the performances of the existing and new organisms, as well as a mix of different organisms in decolorizing dyes. In addition, there is still much room for research in genetically engineered organisms and immobilized organisms, as well as the immobilization of enzymes for dye decolorization. Alongside this, studies related to technical and cost feasibility and environmental impacts of the immobilized biological materials will need to be further investigated. It is also important to understand the fates of decolorized dyes to gain a better picture of whether biological processes are really effective in converting dyes into harmless substances.

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#### Competing Interest

The authors declare that there is no competing interest.

## References

- [1] Solís, M.; Solís, A.; Pérez, H.I.; Manjarrez, N.; Flores, M. (2012). Microbial decolouration of azo dyes: A review. *Process Biochemistry*, 47, 1723–1748. <https://doi.org/10.1016/j.procbio.2012.08.014>.
- [2] Adegoke, K.A.; Bello, O.S. (2015). Dye sequestration using agricultural wastes as adsorbents. *Water Resources and Industry*, 12, 8–24. <https://doi.org/10.1016/j.wri.2015.09.002>.
- [3] Robinson, T.; McMullan, G.; Marchant, R.; Nigam, P. (2001). Remediation of dyes in textile effluent: a critical review on current treatment technologies with a proposed alternative. *Bioresource Technology*, 77, 247–255. [https://doi.org/10.1016/S0960-8524\(00\)00080-8](https://doi.org/10.1016/S0960-8524(00)00080-8).
- [4] Nguyen, T.A.; Juang, R.-S. (2013). Treatment of waters and wastewaters containing sulfur dyes: A review. *Chemical Engineering Journal*, 219, 109–117. <https://doi.org/10.1016/j.cej.2012.12.102>.
- [5] Hethnawi, A.; Nassar, N.N.; Manasrah, A.D.; Vitale, G. (2017). Polyethylenimine-functionalized pyroxene nanoparticles embedded on Diatomite for adsorptive removal of dye from textile wastewater in a fixed-bed column. *Chemical Engineering Journal*, 320, 389–404. <https://doi.org/10.1016/j.cej.2017.03.057>.
- [6] Rauf, M.A.; Salman Ashraf, S. (2012). Survey of recent trends in biochemically assisted degradation of dyes. *Chemical Engineering Journal*, 209, 520–530. <https://doi.org/10.1016/j.cej.2012.08.015>.
- [7] Cotillas, S.; Llanos, J.; Cañizares, P.; Clematis, D.; Cerisola, G.; Rodrigo, M.A.; Panizza, M. (2018). Removal of Procion Red MX-5B dye from wastewater by conductive-diamond electrochemical oxidation. *Electrochimica Acta*, 263, 1–7. <https://doi.org/10.1016/j.electacta.2018.01.052>.
- [8] Gao, Y.; Yang, B.; Wang, Q. (2018). Biodegradation and Decolorization of Dye Wastewater: A Review. *IOP Conference Series: Earth and Environmental Science*, 178, 12013. <https://doi.org/10.1088/1755-1315/178/1/012013>.
- [9] Tripathi, A.; Srivastava, S.K. (2011). Ecofriendly treatment of azo dyes: biodecolorization using bacterial strains. *International Journal of Bioscience, Biochemistry and Bioinformatics*, 1, 37.
- [10] Ali, H. (2010). Biodegradation of Synthetic Dyes—A Review. *Water, Air, & Soil Pollution*, 213, 251–273. <https://doi.org/10.1007/s11270-010-0382-4>.
- [11] Hassan, M.M.; Carr, C.M. (2018). A critical review on recent advancements of the removal of reactive dyes from dyehouse effluent by ion-exchange adsorbents. *Chemosphere*, 209, 201–219. <https://doi.org/10.1016/j.chemosphere.2018.06.043>.
- [12] Imran, M.; Crowley, D.E.; Khalid, A.; Hussain, S.; Mumtaz, M.W.; Arshad, M. (2015). Microbial biotechnology for decolorization of textile wastewaters. *Reviews in Environmental Science and Bio/Technology*, 14, 73–92. <https://doi.org/10.1007/s11157-014-9344-4>.
- [13] Sandhya, S. (2010). Biodegradation of Azo Dyes Under Anaerobic Condition: Role of Azoreductase. In *Biodegradation of Azo Dyes*; Atacag Erkurt, H., Ed.; Springer: Berlin Heidelberg, Germany, Volume 9, pp. 39–57. <https://doi.org/10.1007/978-3-642-00943-4>.
- [14] Newman, M.C. (2019). *Fundamentals of ecotoxicology: the science of pollution*. Routledge: Oxfordshire, United Kingdom.
- [15] Rehman, K.; Shahzad, T.; Sahar, A.; Hussain, S.; Mahmood, F.; Siddique, M.H.; Siddique, M.A.; Rashid, M.I. (2018). Effect of Reactive Black 5 azo dye on soil processes related to C and N cycling. *PeerJ - Life and Environment*, 6, e4802.
- [16] Salleh, M.A.M.; Mahmoud, D.K.; Karim, W.A.W.A.; Idris, A. (2011). Cationic and anionic dye adsorption by agricultural solid wastes: A comprehensive review. *Desalination*, 280, 1–13. <https://doi.org/10.1016/j.desal.2011.07.019>.

- [17] Tang, K.H.D. (2020). A Case Study Of The Environmental Impact Assessment Legislations In Sarawak, Malaysia. *Asia Pacific Journal of Energy and Environment*, 7, 47–54. <https://doi.org/10.18034/apjee.v7i1.273>.
- [18] Textile Industry Wastewater Discharge Quality Standards: Literature Review. (assessed on 1 Marchn 2022) Available online: <https://wastewater.sustainabilityconsortium.org/downloads/textile-industry-wastewater-discharge-quality-standards/>.
- [19] Wang, L.; Ding, X.; Wu, X. (2013). Blue and grey water footprint of textile industry in China. *Water Science and Technology*, 68, 2485–2491. <https://doi.org/10.2166/wst.2013.532>.
- [20] Tang, L.; Yu, J.; Pang, Y.; Zeng, G.; Deng, Y., Wang, J.; Ren, X.; Ye, S.; Peng, B.; Feng, H. (2018). Sustainable efficient adsorbent: Alkali-acid modified magnetic biochar derived from sewage sludge for aqueous organic contaminant removal. *Chemical Engineering Journal*, 336, 160–169. <https://doi.org/10.1016/j.cej.2017.11.048>.
- [21] Holkar, C.R.; Jadhav, A.J.; Pinjari, D.V.; Mahamuni, N.M.; Pandit, A.B. (2016). A critical review on textile wastewater treatments: Possible approaches. *Journal of Environmental Management*, 182, 351–366. <https://doi.org/10.1016/j.jenvman.2016.07.090>.
- [22] Tang, K.H.D.; Angela, J. (2019). Phytoremediation of crude oil-contaminated soil with local plant species. *IOP Conference Series: Materials Science and Engineering*, 495, 12054. <https://doi.org/10.1088/1757-899x/495/1/012054>.
- [23] Tang, K.H.D.; Kristanti, R.A. (2022). Bioremediation of perfluorochemicals: current state and the way forward. *Bioprocess and Biosystems Engineering*. <https://doi.org/10.1007/s00449-022-02694-z>.
- [24] Choong, W.S.; Hadibarata, T.; Yuniarto, A.; Tang, K.H.D.; Abdullah, F., Syafrudin, M.; Al Farraj, D.A.; Al-Mohaimed, A.M. (2021). Characterization of microplastics in the water and sediment of Baram River estuary, Borneo Island. *Marine Pollution Bulletin*, 172, 112880. <https://doi.org/10.1016/j.marpolbul.2021.112880>.
- [25] Tang, K.H.D. (2021). Interactions of Microplastics with Persistent Organic Pollutants and the Ecotoxicological Effects: A Review. *Tropical Aquatic and Soil Pollution*, 1(1), 24–34. <https://doi.org/10.53623/tasp.v1i1.11>.
- [26] Tang, K.H.D.; Awa, S.H.; Hadibarata, T. (2020). Phytoremediation of Copper-Contaminated Water with Pistia stratiotes in Surface and Distilled Water. *Water, Air, & Soil Pollution*, 231, 573. <https://doi.org/10.1007/s11270-020-04937-9>.
- [27] Kalyani, D.C.; Telke, A.A.; Dhanve, R.S.; Jadhav, J.P. (2009). Ecofriendly biodegradation and detoxification of Reactive Red 2 textile dye by newly isolated *Pseudomonas* sp. SUK1. *Journal of Hazardous Materials*, 163, 735–742. <https://doi.org/10.1016/j.jhazmat.2008.07.020>.
- [28] Carvalho, M.C.; Pereira, C.; Gonçalves, I.C.; Pinheiro, H.M.; Santos, A.R.; Lopes, A.; Ferrá, M.I. (2008). Assessment of the biodegradability of a monosulfonated azo dye and aromatic amines. *International Biodeterioration & Biodegradation*, 62, 96–103. <https://doi.org/10.1016/j.ibiod.2007.12.008>.
- [29] Olukanni, O.D.; Osuntoki, A.A.; Gbenle, G.O. (2009). Decolourization of azo dyes by a strain of Micrococcus isolated from a refuse dump soil. *Biotechnology*, 8, 442–448. <https://doi.org/10.3923/biotech.2009.442.448>.
- [30] Ayed, L.; Mahdhi, A.; Cheref, A.; Bakhrouf, A. (2011). Decolorization and degradation of azo dye Methyl Red by an isolated *Sphingomonas paucimobilis*: Biototoxicity and metabolites characterization. *Desalination*, 274, 272–277. <https://doi.org/10.1016/j.desal.2011.02.024>.
- [31] Bhattacharya, A.; Goyal, N.; Gupta, A. (2017). Degradation of azo dye methyl red by alkaliphilic, halotolerant *Nesterenkonia lacusekhoensis* EMLA3: application in alkaline and salt-rich dyeing effluent treatment. *Extremophiles*, 21, 479–490. <https://doi.org/10.1007/s00792-017-0918-2>.

- [32] Sari, I.P.; Simarani, K. (2019). Comparative static and shaking culture of metabolite derived from methyl red degradation by *Lysinibacillus fusiformis* strain W1B6. *Royal Society Open Science*, 6, 190152.
- [33] Pan, H.; Feng, J.; Cerniglia, C.E.; Chen, H. (2011). Effects of Orange II and Sudan III azo dyes and their metabolites on *Staphylococcus aureus*. *Journal of Industrial Microbiology and Biotechnology*, 38, 1729–1738. <https://doi.org/10.1007/s10295-011-0962-3>.
- [34] Singh, R.P.; Singh, P.K.; Singh, R.L. (2014). Bacterial Decolorization of Textile Azo Dye Acid Orange by *Staphylococcus hominis* RMLRT03. *Toxicology International*, 21, 160–166. <https://doi.org/10.4103/0971-6580.139797>.
- [35] Tripathi, A.; Srivastava, S.K. (2011). Biodecolorization of Azo dye, Acid Orange 10, using different bacterial strains. *Proceedings of 2nd International Conferences on Environmental Science and Technology*, 6, V2-253.
- [36] Shah, B.; Jain, K.; Jiyani, H.; Mohan, V.; Madamwar, D. (2016). Microaerophilic Symmetric Reductive Cleavage of Reactive Azo Dye—Remazole Brilliant Violet 5R by Consortium VIE6: Community Synergism. *Applied Biochemistry and Biotechnology*, 180, 1029–1042. <https://doi.org/10.1007/s12010-016-2150-4>.
- [37] Waghmode, T.R.; Kurade, M.B.; Govindwar, S.P. (2011). Time dependent degradation of mixture of structurally different azo and non azo dyes by using *Galactomyces geotrichum* MTCC 1360. *International Biodeterioration & Biodegradation*, 65, 479–486. <https://doi.org/10.1016/j.ibiod.2011.01.010>.
- [38] Meerbergen, K.; Willems, K.A.; Dewil, R.; Van Impe, J.; Appels, L.; Lievens, B. (2018). Isolation and screening of bacterial isolates from wastewater treatment plants to decolorize azo dyes. *Journal of Bioscience and Bioengineering*, 125, 448–456. <https://doi.org/10.1016/j.jbiosc.2017.11.008>.
- [39] Kadam, A.A.; Telke, A.A.; Jagtap, S.S.; Govindwar, S.P. (2011). Decolorization of adsorbed textile dyes by developed consortium of *Pseudomonas* sp. SUK1 and *Aspergillus ochraceus* NCIM-1146 under solid state fermentation. *Journal of Hazardous Materials*, 189, 486–494. <https://doi.org/10.1016/j.jhazmat.2011.02.066>.
- [40] Hai, F.I.; Yamamoto, K.; Nakajima, F.; Fukushi, K. (2008). Removal of structurally different dyes in submerged membrane fungi reactor—Biosorption/PAC-adsorption, membrane retention and biodegradation. *Journal of Membrane Science*, 325, 395–403. <https://doi.org/10.1016/j.memsci.2008.08.006>.
- [41] Gao, T.; Qin, D.; Zuo, S.; Peng, Y.; Xu, J.; Yu, B.; Song, H.; Dong, J. (2020). Decolorization and detoxification of triphenylmethane dyes by isolated endophytic fungus, *Bjerkandera adusta* SWUSI4 under non-nutritive conditions. *Bioresources and Bioprocessing*, 7, 53. <https://doi.org/10.1186/s40643-020-00340-8>.
- [42] Kolekar, Y.M.; Kodam, K.M. (2012). Decolorization of textile dyes by *Alishewanella* sp. KMK6. *Applied Microbiology and Biotechnology*, 95, 521–529. <https://doi.org/10.1007/s00253-011-3698-0>.
- [43] Oturkar, C.C.; Patole, M.S.; Gawai, K.R.; Madamwar, D. (2013). Enzyme based cleavage strategy of *Bacillus lentus* BI377 in response to metabolism of azoic recalcitrant. *Bioresource Technology*, 130, 360–365. <https://doi.org/10.1016/j.biortech.2012.12.019>.
- [44] Guadie, A.; Gessesse, A.; Xia, S. (2018). *Halomonas* sp. strain A55, a novel dye decolorizing bacterium from dye-uncontaminated Rift Valley Soda lake. *Chemosphere*, 206, 59–69. <https://doi.org/10.1016/j.chemosphere.2018.04.134>.
- [45] Mishra, B.; Varjani, S.; Kumar, G.; Awasthi, M.K.; Awasthi, S.K.; Sindhu, R.; Binod, P.; Rene, E.R.; Zhang, Z. (2020). Microbial approaches for remediation of pollutants: Innovations, future outlook, and challenges. *Energy & Environment*, 32, 1029–1058. <https://doi.org/10.1177/0958305X19896781>.



- [46] El-Sheekh, M.M.; Gharieb, M.M.; Abou-El-Souod, G.W. (2009). Biodegradation of dyes by some green algae and cyanobacteria. *International Biodeterioration & Biodegradation*, 63, 699–704. <https://doi.org/10.1016/j.ibiod.2009.04.010>.
- [47] Ishchi, T.; Sibi, G. (2020). Azo dye degradation by *Chlorella vulgaris*: optimization and kinetics. *International Journal of Biological Chemistry*, 14(1), 1–7. <https://doi.org/10.3923/ijbc.2020.1.7>.
- [48] Hadibarata, T.; Yusoff, A.R.M.; Kristanti, R.A. (2012). Acceleration of Anthraquinone-Type Dye Removal by White-Rot Fungus Under Optimized Environmental Conditions. *Water, Air, & Soil Pollution*, 223(8), 4669–4677. <https://doi.org/10.1007/s11270-012-1177-6>.
- [49] Deivasigamani, C.; Das, N. (2011). Biodegradation of Basic Violet 3 by *Candida krusei* isolated from textile wastewater. *Biodegradation*, 22, 1169–1180. <https://doi.org/10.1007/s10532-011-9472-2>.
- [50] Al-Tohamy, R.; Sun, J.; Fareed, M.F.; Kenawy, E.-R.; Ali, S.S. (2020). Ecofriendly biodegradation of Reactive Black 5 by newly isolated *Sterigmatomyces halophilus* SSA1575, valued for textile azo dye wastewater processing and detoxification. *Scientific Reports*, 10, 12370. <https://doi.org/10.1038/s41598-020-69304-4>.
- [51] Xiao, X.; Xu, C.C.; Wu, Y.M.; Cai, P.J.; Li, W.W.; Du, D.L.; Yu, H.Q. (2012). Biodecolorization of Naphthol Green B dye by *Shewanella oneidensis* MR-1 under anaerobic conditions. *Bioresource Technology*, 110, 86–90. <https://doi.org/10.1016/j.biortech.2012.01.099>.
- [52] Prasad, A.S.A.; Rao, K.V.B. (2014). Aerobic biodegradation of azo dye Acid Black-24 by *Bacillus halodurans*. *Journal of Environmental Biology*, 35(3), 549. <http://doi.org/10.1007/s40010-014-0163-3>.
- [53] Jasińska, A.; Soboń, A.; Góralczyk-Bińkowska, A.; Długoński, J. (2019). Analysis of decolorization potential of *Myrothecium roridum* in the light of its secretome and toxicological studies. *Environmental Science and Pollution Research*, 26(25), 26313–26323. <https://doi.org/10.1007/s11356-019-05324-6>.
- [54] Ashrafi, S.D.; Rezaei, S.; Forootanfar, H.; Mahvi, A.H.; Faramarzi, M.A. (2013). The enzymatic decolorization and detoxification of synthetic dyes by the laccase from a soil-isolated ascomycete, *Paraconiothyrium variabile*. *International Biodeterioration & Biodegradation*, 85, 173–181. <https://doi.org/10.1016/j.ibiod.2013.07.006>.
- [55] Das, P.; Banerjee, P.; Zaman, A.; Bhattacharya, P. (2016). Biodegradation of two Azo dyes using *Dietzia* sp. PD1: process optimization using Response Surface Methodology and Artificial Neural Network. *Desalination and Water Treatment*, 57, 7293–7301. <https://doi.org/10.1080/19443994.2015.1013993>.
- [56] Neifar, M.; Chouchane, H.; Mahjoubi, M.; Jaouani, A.; Cherif, A. (2016). *Pseudomonas extremorientalis* BU118: a new salt-tolerant laccase-secreting bacterium with biotechnological potential in textile azo dye decolourization. *3 Biotech*, 6, 107. <https://doi.org/10.1007/s13205-016-0425-7>.
- [57] Verma, A.; Shirkot, P. (2014). Purification and Characterization of Thermostable Laccase from Thermophilic *Geobacillus thermocatenulatus* MS5 and its applications in removal of Textile Dyes. *Scholars Academic Journal of Biosciences*, 2, 479–485.
- [58] Rajhans, G.; Sen, S.K.; Barik, A.; Raut, S. (2020). Elucidation of fungal dye-decolourizing peroxidase (DyP) and ligninolytic enzyme activities in decolourization and mineralization of azo dyes. *Journal of Applied Microbiology*, 129, 1633–1643. <https://doi.org/https://doi.org/10.1111/jam.14731>.
- [59] Haq, I.; Raj, A.; Markandeya. (2018). Biodegradation of Azure-B dye by *Serratia liquefaciens* and its validation by phytotoxicity, genotoxicity and cytotoxicity studies. *Chemosphere*, 196, 58–68. <https://doi.org/10.1016/j.chemosphere.2017.12.153>.

- [60] Ajaz, M.; Rehman, A.; Khan, Z.; Nisar, M.A.; Hussain, S. (2019). Degradation of azo dyes by *Alcaligenes aquatilis* 3c and its potential use in the wastewater treatment. *AMB Express*, 9, 64. <https://doi.org/10.1186/s13568-019-0788-3>.
- [61] Franciscon, E.; Grossman, M.J.; Paschoal, J.A.R.; Reyes, F.G.R.; Durrant, L.R. (2012). Decolorization and biodegradation of reactive sulfonated azo dyes by a newly isolated *Brevibacterium sp. strain VN-15*. *SpringerPlus*, 1, 37. <https://doi.org/10.1186/2193-1801-1-37>.
- [62] El-Sheekh, M.M.; Abou-El-Souod, G.W.; El Asrag, H.A. (2018). Biodegradation of Some Dyes by The Green Alga *Chlorella vulgaris* and the *Cyanobacterium Aphanocapsa elachista*. *Egyptian Journal of Botany*, 58, 311–320. <https://doi.org/10.21608/ejbo.2018.2675.1145>.
- [63] Tian, F.; Guo, G.; Zhang, C.; Yang, F.; Hu, Z.; Liu, C.; Wang, S.W. (2019). Isolation, cloning and characterization of an azoreductase and the effect of salinity on its expression in a halophilic bacterium. *International Journal of Biological Macromolecules*, 123, 1062–1069. <https://doi.org/10.1016/j.ijbiomac.2018.11.175>.
- [64] Pratiwi, D.; Prasetyo, D.J.; Poeloengasih, C.D. (2019). Adsorption of Methylene Blue dye using Marine algae *Ulva lactuca*. *IOP Conference Series: Earth and Environmental Science*, 251, 12012. <https://doi.org/10.1088/1755-1315/251/1/012012>.
- [65] Vats, A.; Mishra, S. (2017). Decolorization of complex dyes and textile effluent by extracellular enzymes of *Cyathus bulleri* cultivated on agro-residues/domestic wastes and proposed pathway of degradation of Kiton blue A and reactive orange 16. *Environmental Science and Pollution Research*, 24, 11650–11662. <https://doi.org/10.1007/s11356-017-8802-2>.
- [66] Bankole, P.O.; Adekunle, A.A.; Obidi, O.F.; Chandanshive, V.V.; Govindwar, S.P. (2018). Biodegradation and detoxification of Scarlet RR dye by a newly isolated filamentous fungus, *Peyronellaea prosopidis*. *Sustainable Environment Research*, 28, 214–222. <https://doi.org/10.1016/j.serj.2018.03.001>.
- [67] Erden, E.; Kaymaz, Y.; Pazarlioglu, N.K. (2011). Biosorption kinetics of a direct azo dye Sirius Blue K-CFN by *Trametes versicolor*. *Electronic Journal of Biotechnology*, 14(2), 3. <http://doi.org/10.2225/vol14-issue2-fulltext-8>.
- [68] Ambrósio, S.T.; Vilar Júnior, J.C.; Da Silva, C.A.A.; Okada, K.; Nascimento, A.E.; Longo, R.L.; Campos-Takaki, G.M. (2012). A Biosorption Isotherm Model for the Removal of Reactive Azo Dyes by Inactivated Mycelia of *Cunninghamella elegans* UCP542. *Molecules*, 17, 452–462. <https://doi.org/10.3390/molecules17010452>.
- [69] Lee, K.K.; Tang, K.H.D. (2020). Agaricales (Gilled Mushrooms) as Biosorbents of Synthetic Dye. *Malaysian Journal of Medicine and Health Sciences*, 16, 10–17.
- [70] Krishnamoorthy, R.; Jose, P.A.; Ranjith, M.; Anandham, R.; Suganya, K.; et al. (2018). Decolourisation and degradation of azo dyes by mixed fungal culture consisted of *Dichotomomyces cejpui* MRCH 1-2 and *Phoma tropica* MRCH 1-3. *Journal of Environmental Chemical Engineering*, 6, 588–595. <https://doi.org/10.1016/j.jece.2017.12.035>.
- [71] Safarik, I.; Rego, L.F.T.; Borovska, M.; Mosiniewicz-Szablewska, E.; Weyda, F.; Safarikova, M. (2007). New magnetically responsive yeast-based biosorbent for the efficient removal of water-soluble dyes. *Enzyme and Microbial Technology*, 40, 1551–1556. <https://doi.org/10.1016/j.enzmictec.2006.10.034>.
- [72] Dixit, S.; Garg, S. (2019). Development of an efficient recombinant bacterium and its application in the degradation of environmentally hazardous azo dyes. *International Journal of Environmental Science and Technology*, 16, 7137–7146. <https://doi.org/10.1007/s13762-018-2054-7>.
- [73] Sun, J.; Li, Y.; Hu, Y.; Hou, B.; Xu, Q.; Zhang, Y.; Li, S. (2012). Enlargement of anode for enhanced simultaneous azo dye decolorization and power output in air-cathode microbial fuel cell. *Biotechnology Letters*, 34, 2023–2029. <https://doi.org/10.1007/s10529-012-1002-8>.
- [74] Fang, Z.-M.; Li, T.-L.; Chang, F.; Zhou, P.; Fang, W.; Hong, Y.Z.; Zhang, X.C.; Peng, H.; Xiao, Y.Z. (2012). A new marine bacterial laccase with chloride-enhancing, alkaline-dependent activity



- and dye decolorization ability. *Bioresource Technology*, 111, 36–41. <https://doi.org/10.1016/j.biortech.2012.01.172>.
- [75] Eslami, M.; Amoozegar, M.A.; Asad, S. (2016). Isolation, cloning and characterization of an azoreductase from the halophilic bacterium *Halomonas elongata*. *International Journal of Biological Macromolecules*, 85, 111–116. <https://doi.org/10.1016/j.ijbiomac.2015.12.065>.
- [76] Morsy, S.A.G.Z.; Ahmad Tajudin, A.; Ali, M.S.M.; Shariff, F.M. (2020). Current Development in Decolorization of Synthetic Dyes by Immobilized Laccases. *Frontiers in Microbiology*, 11, 572309. <https://doi.org/10.3389/fmicb.2020.572309>.
- [77] Al-Fawwaz, A.T.; Abdullah, M. (2016). Decolorization of methylene blue and malachite green by immobilized *Desmodesmus* sp. isolated from North Jordan. *International Journal of Environmental Science and Development*, 7, 95. <http://doi.org/10.7763/IJESD.2016.V7.748>.
- [78] Alam, M.Z.; Khan, M.J.H.; Kabbashi, N.A.; Sayem, S.M.A. (2018). Development of an Effective Biosorbent by Fungal Immobilization Technique for Removal of Dyes. *Waste and Biomass Valorization*, 9, 681–690. <https://doi.org/10.1007/s12649-016-9821-9>.
- [79] Nguyen, T.A.; Fu, C.-C.; Juang, R.-S. (2016). Effective removal of sulfur dyes from water by biosorption and subsequent immobilized laccase degradation on crosslinked chitosan beads. *Chemical Engineering Journal*, 304, 313–324. <https://doi.org/10.1016/j.cej.2016.06.102>.
- [80] Ma, H.-F.; Meng, G.; Cui, B.-K.; Si, J.; Dai, Y.-C. (2018). Chitosan crosslinked with genipin as supporting matrix for biodegradation of synthetic dyes: Laccase immobilization and characterization. *Chemical Engineering Research and Design*, 132, 664–676. <https://doi.org/10.1016/j.cherd.2018.02.008>.
- [81] Zhang, W.; Yang, Q.; Luo, Q.; Shi, L.; Meng, S. (2020). Laccase-Carbon nanotube nanocomposites for enhancing dyes removal. *Journal of Cleaner Production*, 242, 118425. <https://doi.org/10.1016/j.jclepro.2019.118425>.
- [82] Tang, K.H.D.; Law, Y.W.E. (2019). Phytoremediation of soil contaminated with crude oil using *Mucuna Bracteata*. *Research in Ecology*, 1, 20-30. <http://doi.org/10.30564/re.v1i1.739>.



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